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Review papers

Application of remote sensing to water environmental processes under a changing climate

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ABSTRACT

Remote sensing, as a crucial method to obtain information on water environmental processes, has become a major source of data, particularly of water environment and water resources, which are sensitive to global climate change. The bibliometric analysis provided here shows the research characteristics and developments of remote sensing-based observations of water environmental processes under a changing climate from 2000 to 2018. Visualized knowledge mapping is introduced to investigate the development status, scientific collaboration, involved disciplines, research hotspots and emerging trends of this field. The breadth and depth of remote sensing application in water environmental process studies have improved significantly as the number of related publications rose at an average annual growth rate of 15.97% in the 21st century. The United States and China were the leading contributors with the largest number of publications and all of the top 15 most active institutions. In addition, this field is a highly interdisciplinary field that covers a wide range of interests, from water resources to environmental science, geology, engineering, ecology, and agriculture. The application of remote sensing technology has significantly promoted the estimation of evapotranspiration and soil moisture, thereby offering a more complete perspective to the understanding of the water cycle. Additionally, climate change and its complex interactions with water environmental processes, including the occurrence of drought events, are of great significance and require special attention.

1. Introduction

Climate change, which may lead to changes in water-resource availability, the frequency and intensity of tropical storms, floods, and droughts, and an amplification of warming through the water vapor feedback, exerts tremendous influences on water environmental processes (Allen and Ingram, 2002; Hagemann et al., 2012; Schewe et al., 2014). These influences have become a global concern of hydrologists and a challenging environmental issue due to its threat to the production and life of human society. Anthropogenic climate change is expected to increase the frequency and intensity of hydrological extremes (Donat et al., 2016; Easterling et al., 2000; Trenberth, 2011), which will directly affect drinking water supplies, wetland function, crop growth, human life and so on (Van Loon, 2015). Spatial and temporal redistributions of water resources might occur, thereby changing the utilization ratio of water resources, the snowmelt season, the growth condition of vegetation and groundwater discharge (Barnett et al., 2005; Kundzewicz et al., 2008; Oki and Kanae, 2006; Ouyang et al., 2015; Piao et al., 2010; Vörösmarty et al., 2000). Therefore, the primary role of understanding water environmental processes under changing climatic conditions is to ensure maintenance of the water supply for human consumption while improving adaptation strategies that foster harmony between humans and nature.

Traditional observations of the water cycle are generally based on single-point measurements with several drawbacks, such as the sparse spatial and temporal coverage of monitoring sites and deficiencies over many parts of the world (Ouyang et al., 2016a, 2016b; Kidd et al., 2017). Problems in data acquisition are further accentuated in regard to

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prediction in ungauged regions or when there is considerable spatial variability in a given watershed (Yadav et al., 2007). Remote sensing technology addresses these deficiencies by providing data with more spatially homogeneous and temporally complete coverage. With current remote sensing technology, most constituent variables of water environmental processes are observable at varying spatiotemporal resolution and accuracy (i.e., precipitation, snow and ice, terrestrial water storage), and ungauged basins can also be explored in ways that previous technology was not capable (Chen et al., 2013; Glenn et al., 2007; Hao et al., 2013; Hou et al., 2014; Immerzeel et al., 2009; Kornelsen and Coulibaly, 2013; Ouyang et al., 2012; Reichle, 2008; Yang et al., 2000; Zhu et al., 2016). Over the last two decades, the study of water environmental processes using remote sensing techniques has advanced considerably. It is necessary to understand the key advances of remote sensing application and what transformation has been experienced.

Bibliometrics emerged in the early 20th century and has developed into a visualization analysis method based on the co-citation network (Chen 2004; Merigó and Yang, 2017; Wang and Xu, 2016). In recent years, it has been widely applied to assess the maturity and vitality of a specific field due to the ability to visually demonstrate the intellectual structures, development states and research hotspots based on a time series of networks derived from publications (Yang et al., 2018). The purpose of this study is to comprehensively and systematically provide a bibliometrics review of the research on remote sensing application to water environmental processes in the context of climate change. More specifically, CiteSpace was used to conduct a more detailed analysis and offer an in-depth and structured review of the global expansibility. The status of remote sensing application in watershed processes under the changing climate was evaluated for the period of 2000–2018. The overall research status and trends were investigated in addition to scientific collaboration and the involved disciplines. Then, the hotspots and evolution of this field were explored respectively for three periods. The analyses of hotspots and emerging trends in this paper are not limited to the results retrieved from Citespace; instead, we applied an expansive review that included additional valuable literature on the basis of the database, aiming to provide a comprehensive and objective review. The method and result of this article may serve as a potential guide for future study.

2. Data acquisition and methods

2.1. Data collection and processing

The data retrieval source for the analysis was the Web of Science Core Collection (WoSCC), which includes the world's leading journals of science and technology. The search words included the following: TS = ((remote* sens*) AND (basin OR watershed) AND (hydrolog* OR (run*off OR stream) OR (precipitation OR rainfall OR snow)) AND (water OR (water *source)) AND ((climat* chang*) OR (climat* dynamics) OR (temperature))). The publications that mention any of these keywords and its variants (with "*") in their titles, abstracts and keyword lists were included. This query generated 1037 records for the period of 1960–2018. The whole records including titles, abstracts, and cited references were then exported to CiteSpace for subsequent analysis.

2.2. Bibliometrics analysis

CiteSpace is a Java-based scientific visualization software package for detecting and visualizing research front and intellectual bases developed by Dr. Chaomei Chen (2006) with various functions for identifying the major topic areas, finding hotspot issues and detecting emerging trends. In CiteSpace, contributing countries can help identify and visualize major contributing factors for the evolution of the hospitality knowledge map. Hot research topics and frontline research in the hospitality field were identified based on frequency of popular keywords used in journal articles. To better understand the development status at a global scale, ArcGIS was employed for the retrieval and to plot the worldwide geographic distribution of countries. The keyword co-word networks were designed to identify hot research topics based on the frequency of keywords. In viewing the maps, a node represents one item and pivotal point with high betweenness centrality is highlighted with a purple ring in order to stand out in a visualized network. The betweenness centrality is defined in the following Eq. (1).

$$Centralit(node_i) = \sum_{i \neq j \neq k} \frac{\rho_{jk}(i)}{\rho_{jk}} \quad (1)$$

In the Eq. (1), ρ_{jk} represents the number of shortest paths between node j and node k, and ρ_{jk} (i) is the number of those paths that pass through node i. At the document level, the importance of each document in a co-citing network can be partially evaluated by the indicator betweenness centrality. An analysis of highly cited papers was also conducted as an effective supplement to the research hotspots. Based on this, burst detection was applied to identify the rapidly growing themes within the last five years.

3. Results and discussion

3.1. Temporal development analysis

Since the first successful Low-Earth orbital weather satellite, Television and Infrared Observation Satellites (TIROS-1) launched by NASA on April 1, 1960, a new era of earth observations was coming (Wexler and Fritz, 1960). And after the 1990s, with the popularization of remote sensing technology and methods, remote sensing has been widely used in watershed management. During this period, the related remote sensing application in hydrology and water resource research started. These early research briefly demonstrated the principles of remote sensing technology, and the applications of remote sensing data in precipitation, evapotranspiration, snow cover, soil moisture and water resource management. Over the last 19 years, the study of the changing water cycle and climate gained momentum with the launch of NASA's Earth Observing System (EOS) and other satellite platforms. Two ascent curves describe a steeper growth in the annual number of papers and the annual sum of times cited synchronously from 1991 to 2018 (Fig. 1). The papers published in the last 19 years accounted for 96.6% of the total publications, with a growth rate of 15.97%. This paper emphasizes the development of the more recent and near-future remote sensing observations in advancing our understanding of water environmental processes under the changing climate, thus we refined the database to 1004 records (i.e., those published from 2000 to 2018) for subsequent analysis.

As for the number of publications, the United States (390), China (274) and Germany (75) were the top three contributing countries, together accounting for 73.60% of the total number of publications. These clusters of countries are consistent with the fact that these regions house a large number of authors and academic institutions.

3.2. Scientific collaboration analysis

Approximately 1260 institutions have contributed to the related research and the top 15 most active institutions are highlighted (Fig. 2d). The Chinese Academy of Science (CAS) led the institutional activity, producing 159 total articles, with a total of 2110 citations. Here, the related research in China tends to combine modern technology methods and consideration of the national practical needs, which thereby promoted the rapid growth of research in CAS from 2000 through 2018. Although the total number of publications emanating from the National Aeronautics and Space Administration (NASA) and University System of Maryland are both less than that from CAS, the total number of citations (3035 and 2273, respectively) of their papers

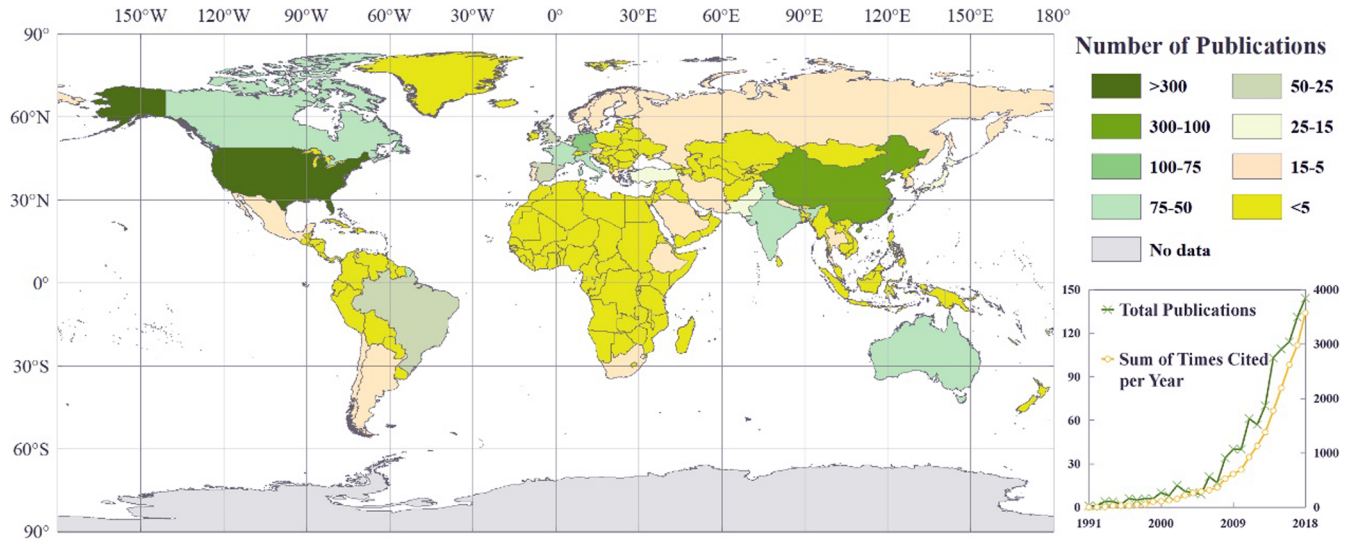

Fig. 1. Characteristics of annual publications and the global geographic distribution of publications.

are higher than that of CAS, which indicates a greater academic influence in this field. Meanwhile, the total publication related to this field from University System of Maryland ranked 15th, with 81 citations per publication, which is the highest average citation number among the top 15 institutions.

This section further analyzed the longitudinal change of the institutional collaboration networks from 2000 to 2018 (Fig. 2). The larger nodes indicate more publications while the brighter links between nodes indicate newer collaboration relationships. Through time, the lines between institutions become denser, which indicates that the

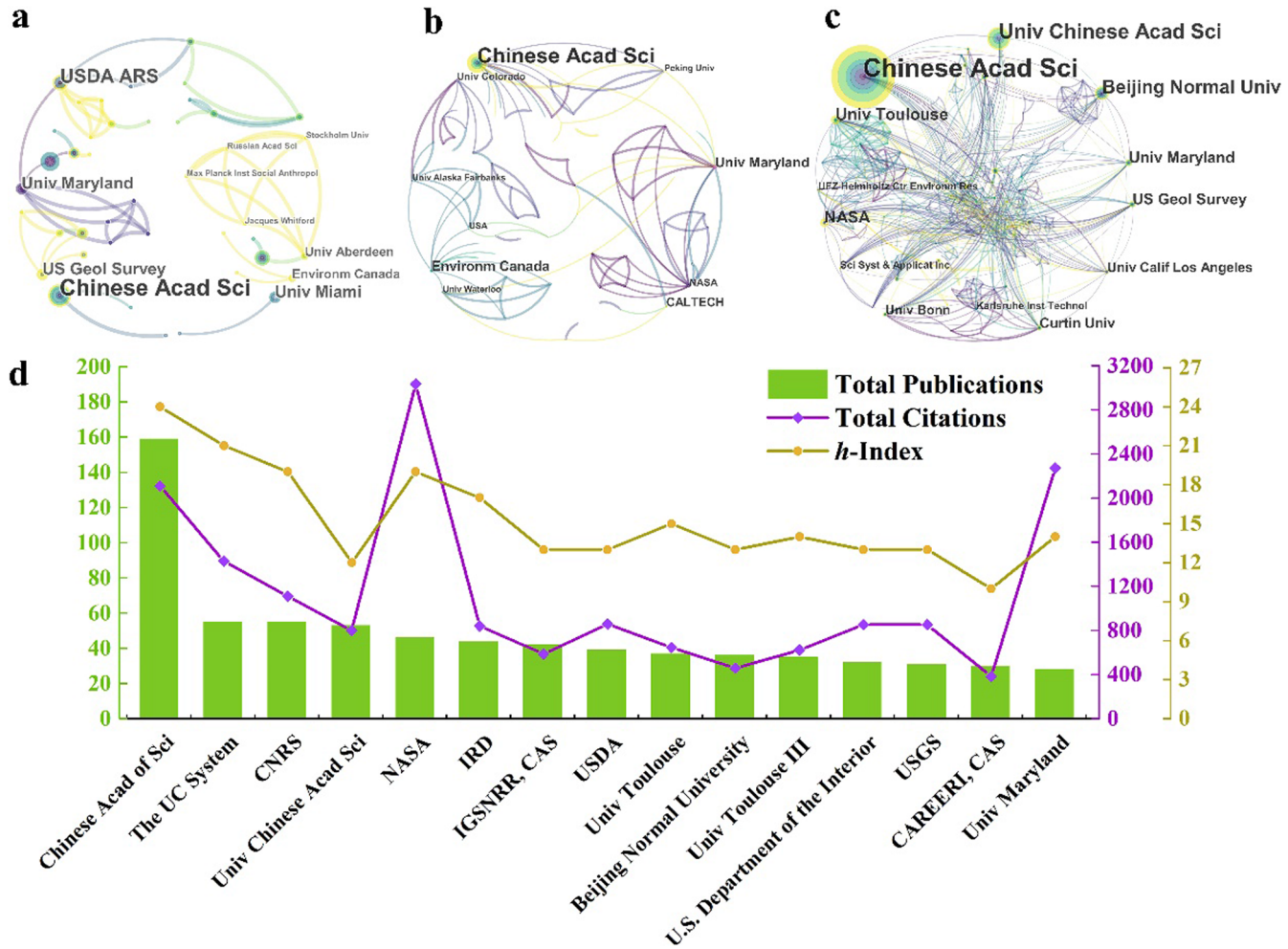

Fig. 2. Scientific collaboration networks of institutions during (a) 2000–2005, (b) 2006–2011, and (c) 2012–2018. (d) The growth trend of publications, citations and h-index of the top 15 institutions.

study and the related climate factors using remote sensing technology is still one of the most important environmental problems worldwide and will remain as a challenge in the near future. For the influence of institutions, this can also be extracted by the centrality of the institutions from the collaboration networks. No definitive leader emerged from 2000 to 2005. However, University System of Maryland (Centrality, 0.16) and Environment Climate Change Canada (Centrality, 0.12) were relatively more influential than others, while other institutions, such as CAS, and University of Colorado increased in influence during 2006–2011. Meanwhile, CAS, Université de Toulouse, Beijing Normal University, University System of Maryland and Curtin University exhibited by far the highest centrality in the last seven years. Other leading institutions from 2012 and 2018 include NASA, U.S. Geological Survey, University of California, Los Angeles. Overall, the active institutions show higher cooperation, but the collaborations between institutions among different countries have remained relatively limited until present. Promoting international collaboration is crucial for improving the accuracy and consistency of satellite data sets.

3.3. Involved disciplines analysis

The annual top 50 common subject categories were selected for the subject category co-occurrence analysis, which indicated that the research of water environmental processes using remote sensing under changing climate involved 49 disciplines. The subject category information was extracted from SU field tags of Web of Science database by CiteSpace and then analyzed. Water resources (publications, 375), Environmental Science & Ecology (283), and Geology (279) are the top three related subjects. The approaches, contents and applications of this field are shared by numerous research domains, such as “Imaging Science and Photographic Technology”, “Meteorology & Atmospheric Science”, and “Marine and Freshwater Biology” (Fig. 3).

The centrality of related publications in the abovementioned subject categories showed that the gravity center of this field revolves around environmental sciences (Fig. 4). Remarkably, the continuous understanding of water environmental processes via remote sensing technology played a vital role in the practical application of agricultural management (Crow et al., 2008). The research of this filed was a highly interdisciplinary field that covered a wide range of interests, from water resources to environmental science, geology, engineering, ecology, and agriculture.

4. Research hotspots and evolution of three periods

The entire time interval of 2000 to 2018 was divided into three periods, and the top 50 keywords in each year were selected for analysis. The size of the node indicates how many times the associated keyword has been used. The links between nodes indicate that two relevant keywords appeared together in an article, which is a graph-theoretical property to understand how keywords and different thematic trends interact with each other. As shown in Fig. 5–7, the three stages of research nodes increased gradually, and the cross fusion of each cluster was significantly enhanced. These results demonstrated that the related studies in this field were constantly expanded and developed.

Fig. 5 depicts the simple network of the most frequent keywords during the period of 2000–2005. After “remote sensing” and “basin”, the three most frequently used keywords are “model”, “temperature” and “soil moisture”. “Model” has always been the core content of watershed hydrological process research, ranking second in this period. Since 1980s, hydrological models have gradually developed to distributed hydrological models (Abbott et al., 1986; Beven and Kirkby, 1979). However, due to the limitations of computation ability and data acquisition technology, the development is relatively slow. Because of the emergence of digital elevation model and massive remote sensing image data, distributed hydrological modelling has undergone a rapid expansion in the 21st century. Most of constituent variables and related essential climate variables in hydrological cycle such as precipitation, temperature, water vapour, soil moisture, evapotranspiration, vegetation cover, ground water and glacier are now available for hydrological modeling via remote sensing (Mendoza et al.,2002; Schmugge et al., 2002). Substantial progress had been made in algorithm development of land surface temperature (LST) during this period. Compared with split-window algorithms (Sobrino et al., 1994), multichannel and multiangle retrieval methods with better accuracy were developed (Sun and Pinker, 2003). “Soil moisture” remained a hot research topic, ranked 5th during 2000–2005. Since the launch of Aqua in May 2002, the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) has provided reliable data of soil moisture (Njoku et al., 2003). In this period, obtain extensive ground truth information and combined with hydrologic modeling, had been key to understanding and reducing the microwave model and retrieval uncertainties caused by vegetation and roughness effects at satellite footprint scales. Microwave models that integrated with land surface hydrologic models can provide a combined framework for direct assimilation of AMSR-E

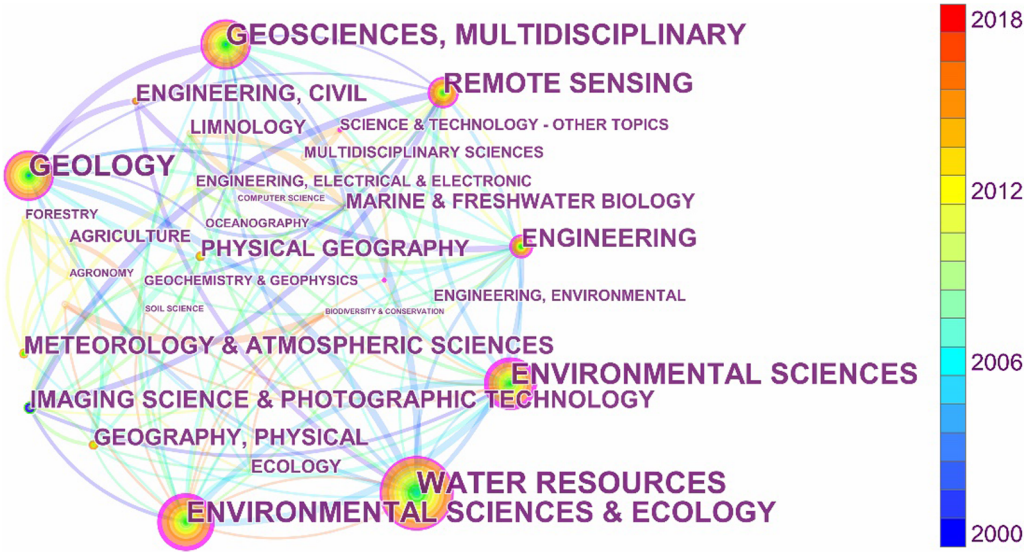

Fig. 3. Network of co-occurring subject categories.

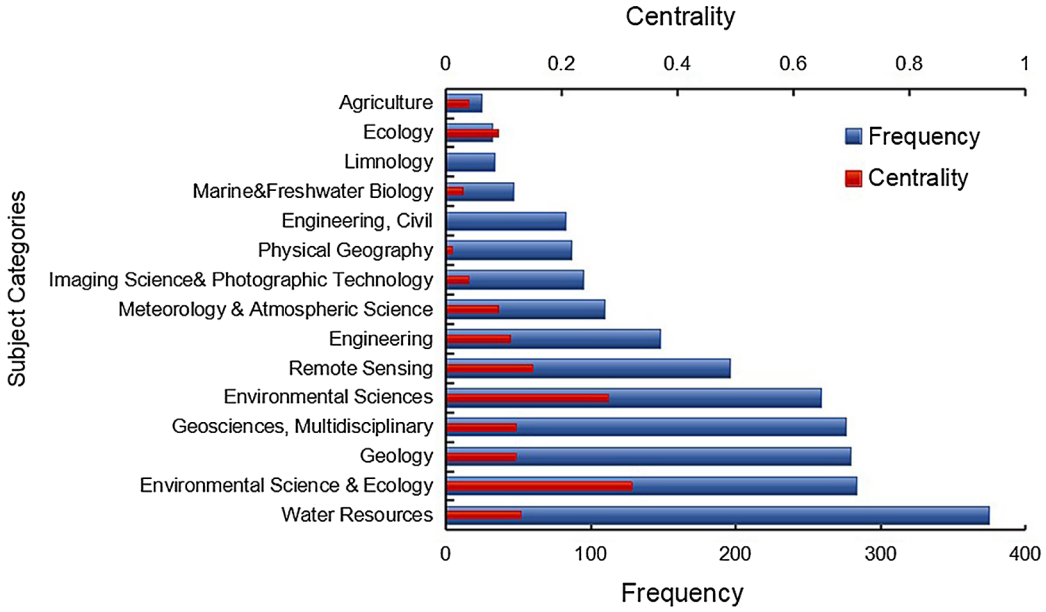

Fig. 4. The Centrality and Frequency of the top 15 subject categories.

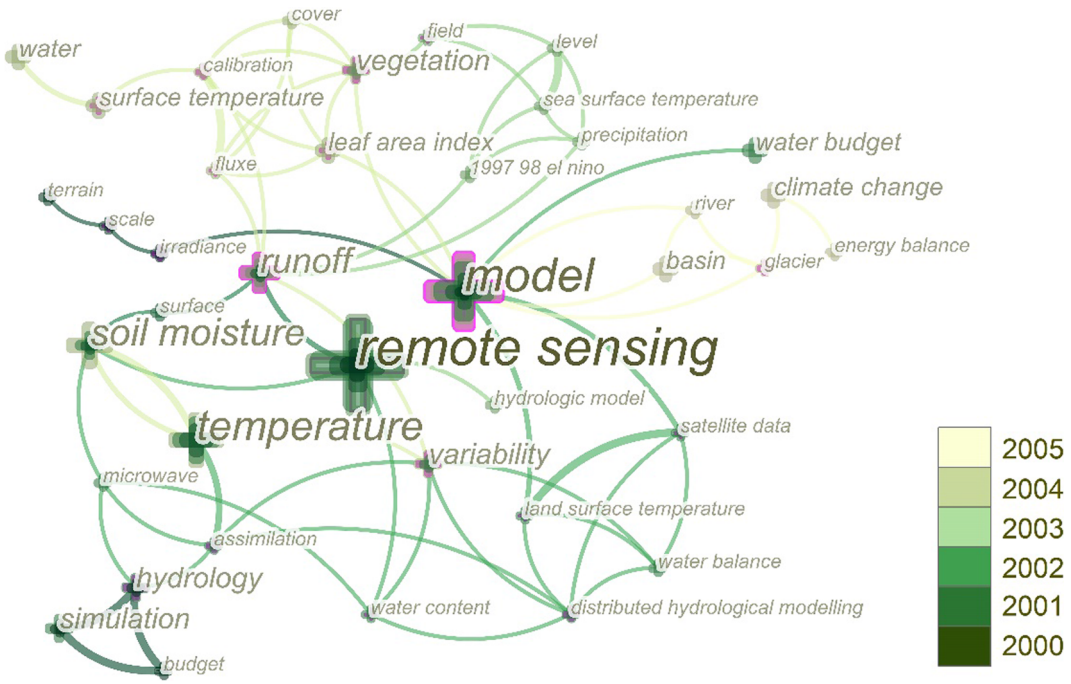

Fig. 5. Network map of remote sensing applications to water environmental processes under changing climate from 2000 to 2005.

brightness temperature data. In addition, the term “vegetation” has a high centrality than others and many research theme revolve around it, such as “cover” and “leaf area index”. In vegetation phenology, climate-driven variations, particularly warming induced by increasing atmospheric greenhouse gases, can have major impacts on the functioning of terrestrial ecosystems by altering carbon, water and energy balances (Matthews et al., 2004). Exploring the relationships between vegetation phenology and climate variability can improve our understanding of how ecosystems will react to climate change and affect hydrological processes governing the water balance. Two satellites, Terra and Aqua with MODerate resolution Imaging Spectroradiometer (MODIS), were launched on December 18, 1999 and May 4, 2002, respectively. These two satellites have provided new data for monitoring vegetation change. Therefore, during this period, many efforts primarily explored the applications of MODIS data for vegetation coverage change monitoring, land cover classification and estimation of net primary productivity. The results indicated that the MODIS-based vegetation index performed with higher fidelity than AVHRR-NDVI and was more sensitive to the seasonal phenology (Huete et al., 2002). These developments laid the foundation for analyzing the watershed underlying surface condition. Studies during this phase appeared to better the understanding of one single hydrological element due to the launch of new satellites and the development of algorithms.

With the increase of algorithms and satellite products, more diversified and integrated watershed process research were achieved (Fig. 6). During this process, “climate change” experienced an increase from 8th to 2th. An increasing number of studies addressed the issue of climate change and its impacts. “runoff”, “scale” and “water resource”

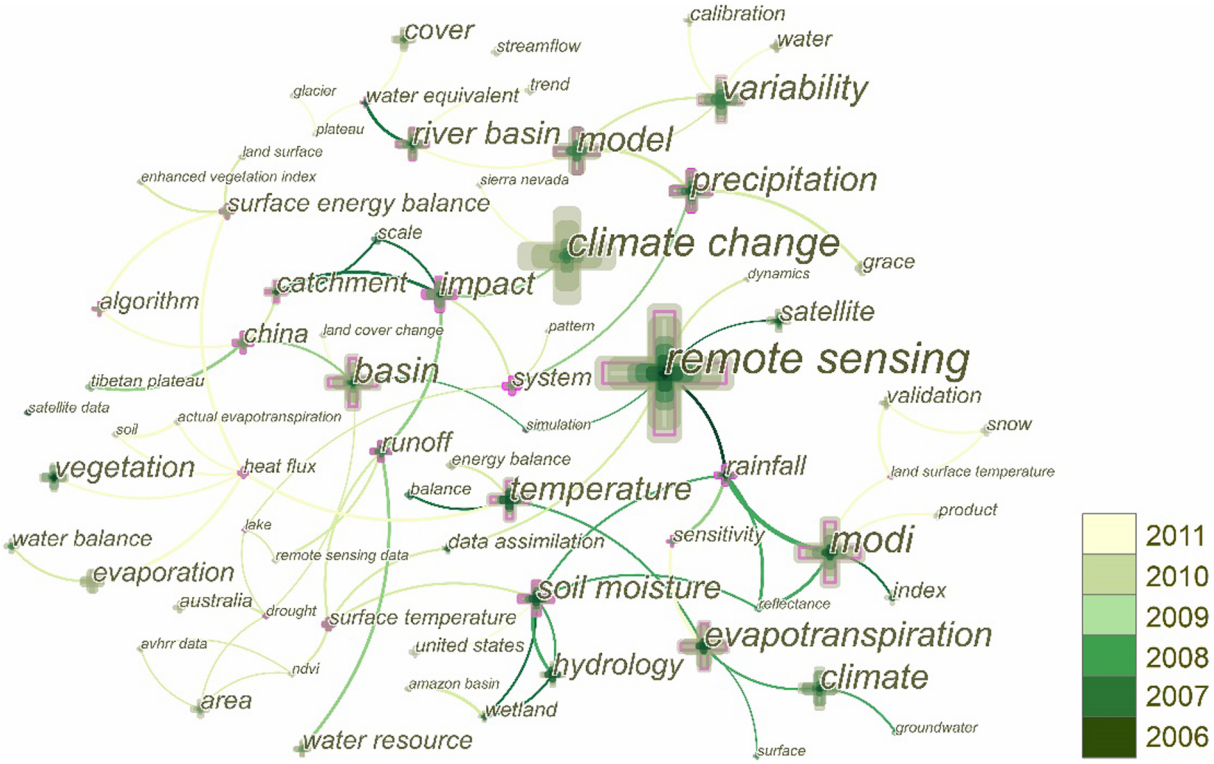

Fig. 6. Network map of remote sensing application to water environmental processes under changing climate from 2006 to 2011.

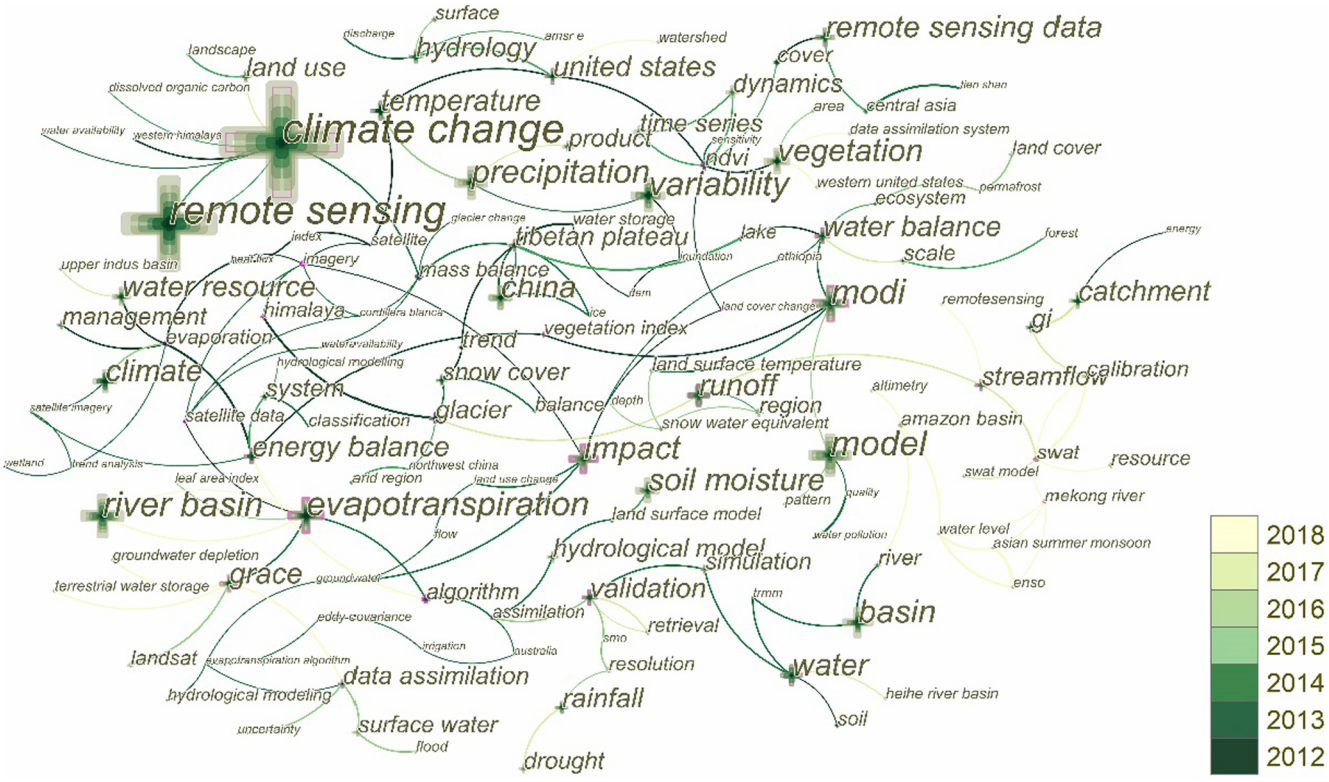

Fig. 7. Network map of remote sensing application to water environmental processes under changing climate from 2012 to 2018.

are the major topic of inquiry in climate change impact study. In this period, the current development in water resources is very sensitive to land use and the spreading and intensification of human activities. Indeed, land use changes such as those caused by urban expansion and deforestation activities have changed the hydrological properties of land surfaces globally (Alcamo et al., 2007). In order to quantify the impacts of such changes on the future availability of water resources, many large-scale hydrological model tools have been used to accurately estimate climate variability and land surface processes governing evapotranspiration and total runoff in agricultural, forest and urban

regions. However, substantial uncertainty regarding variation of runoff remains because of differences in responses across multiple scales, managing water resource still requires new understanding of interactions and feedback at different scales (Huntington, 2006). The estimation of evapotranspiration (ET) received growing attention with a rank advancement jump into the top 5. Traditional estimation methods, including empirical modeling, were difficult to apply to the watersheds with complex underlying surfaces. On the basis of the continuous understanding of vegetation characteristics and land surface temperature from previous period, many methods have been developed to estimate ET from satellite data in this period. One of the most well-known algorithms was developed and improved by Mu et al., (2007, 2011), which offered an improved formation of near-real-time, 8-day and annual ET. The improved ET product can provide information for water resource management and reduce the cost of irrigation projects (Teuling et al., 2009), as well as address pressing questions about the water cycle and its forcing mechanisms (Venturini et al., 2008). "Model" continues to be a frequently-used tool for watershed hydrological process researches, maintained the 6th position in the ranking. With the increases in types of remote sensing products, there has been a growing acceptance of remote sensing products as input data for hydrological modeling. For instance, using TRMM rainfall data, Collischonn et al., (2008) found that TRMM rainfall estimation reproduces the rainfall regime of Tapajós basin fairly well, particularly when there is a sever lack of conventional rain measurements, data from satellite can be a helpful source for rainfall-runoff simulation. As for calibrating distributed hydrological models, Immerzeel and Droogers (2008) showed that the r^2 between monthly sub-basin simulated and measured actual ET was increased from 0.40 to 0.81 by incorporating remote sensing derived ET in the model calibration. Moreover, multivariate observations in hydrological data assimilation indicate that model parameter optimization by single factor observation causes errors between other non-quantitative variables of the model. There are still considerable uncertainties in improving model performance. Currently, the application of multielement observations has proven to be effective for achieving improvements in modeling and prediction of watershed hydrological processes (Liu and Gupta, 2007; Reichle, 2008; Wu et al., 2018). These developments at this stage appeared as a transition in that the research objects are not limited to one certain single hydrological factor but rather multiple elements to be used for more complex parameter optimization of hydrological simulations.

The breadth and depth of research on water environmental processes using remote sensing increased significantly with more nodes and links in the period of 2012–2018 (Fig. 7). "Climate change" exhibited a higher frequency than the previous two periods, ranking first in the latest period. Evidence of increasing intense precipitation events both on the regional and global scales supported the contention that several aspects of the hydrological cycle are intensifying as a result of global climate warming (Donat et al., 2016; Ouyang et al., 2010). Therefore, the growing concern has triggered research on the mechanisms and extent of climate change on water cycle. Long-term changes in water environmental processes are driven by interrelated natural processes and human activities. None of these factors can be considered separately given their complex relationship with one another. As a result, there were numerous studies focused on the effect of climate change and land management on water environmental processes and efforts to distinguish the contribution of different driving factors. "Mass balance", "Western Himalaya", "China" and "Tibetan Plateau" were the most frequent keywords with climate change. Permafrost thawing and glacier retreat are projected to increase with the rising global temperatures, changing the water supply for billions of people and threatening residential safety. Therefore, glacier variation monitoring, climate change and its impact on the water cycle in the third pole have attracted increasing attention during the latest period.

"Evapotranspiration" remained among the top 10 most frequently used keywords during 2012–2018, since it is still a challenge to estimate ET accurately at watershed level due to ET varies at different land cover. Several research has already systematically reviewed ET estimation and its ability to improve understanding of water cycle (Herman et al., 2018; Long et al., 2014; Wang and Dickinson, 2012). In addition, the keywords linked with ET, such as "GRACE" and "river basin" were the main content of the ET studies. Efficient water resource management depend heavily on quantifying water storage changes. Therefore, many studies addressed water storage variations using satellite ET data and efforts to evaluate the potential of water budget closure without field experiments and ground-based measurement. The node "precipitation" remained 8th in 2012–2018 due to its significance of regional hydrologic cycle. Accurate estimation of precipitation can help manage the supply and demand of sustainable water resources and also as a critical input variable for hydrologic modeling and climate studies which are common tools to assess water-related risks, such as droughts, floods and monitor water resources. Therefore, availability and accurate estimation of precipitation is crucial for demand management, flood forecasting and drought preparedness. With the advance of infrared and microwave instruments, a large number of meteorological data sets, especially global precipitation data sets have emerged, including satellite-based and reanalysis data sets. Although the warming trend and its influences have been quantified on the basis of these multiple data sets, different products had large uncertainties (e.g., deviations of 300 mm in annual precipitation) in the magnitude and variability of precipitation (Hall et al., 2002). Therefore, data validation in precipitation products, as well as uncertainty analysis have gained in popularity in watershed research. In addition, the resolution of current products is typically lower than 5 km × 5 km, presenting a continuing challenge for small watershed research. With the development of sensor and platform technology of remote sensing, the datasets and products showed a considerable increase in terms of quantity and variety, which thus promoted the combined application of multiband, multisensor and multisatellite data.

Soil moisture is another major area of remote sensing application for hydrological process, as the frequency of "soil moisture" ranked 11th in 2012–2017. In general, AMSR-E soil moisture products were the most common choice due to its relatively long service time and data availability. With the launch of the Soil Moisture Ocean Salinity (SMOS) mission in 2009 and the Soil Moisture Active Passive (SMAP) mission in 2015, passive microwave L-band remote sensing was considered to be one of the most promising approaches to monitoring soil moisture (Entekhabi et al., 2010; Jiao et al., 2014; Kerr et al., 2010). These two missions allowed for soil moisture retrieval from space at a dramatically higher level, which motivated a shift in attention to exploring multisensor fusion as well as improving spatiotemporal resolution and the quality of products for hydrologic studies. This progress promoted the development of soil moisture data sets using multitemporal, multisensor and multisatellite remote sensing data, which also provided a reliable data source for climate research. In addition, the investigation of soil moisture and climate interactions is a very vibrant research field, which lies at the interface between several major scientific disciplines. Despite current limitations due to the lack of ground observations in several regions of the globe, major advances can be expected in the coming years. This may require the joint investigation of various disciplines, and the combination and comparison of modelling and observational datasets, as well as the conducting of numerical and field experiments. Overall, the application of remote sensing in water environmental processes studies has shifted from simple data acquisition for single hydrologic variables toward a higher stage of data self-verification for integrated research of watershed processes and the interacting mechanisms between different processes.

4.1. Co-citation analysis of high citation papers

Based on the highly cited papers and clustering analysis of co-

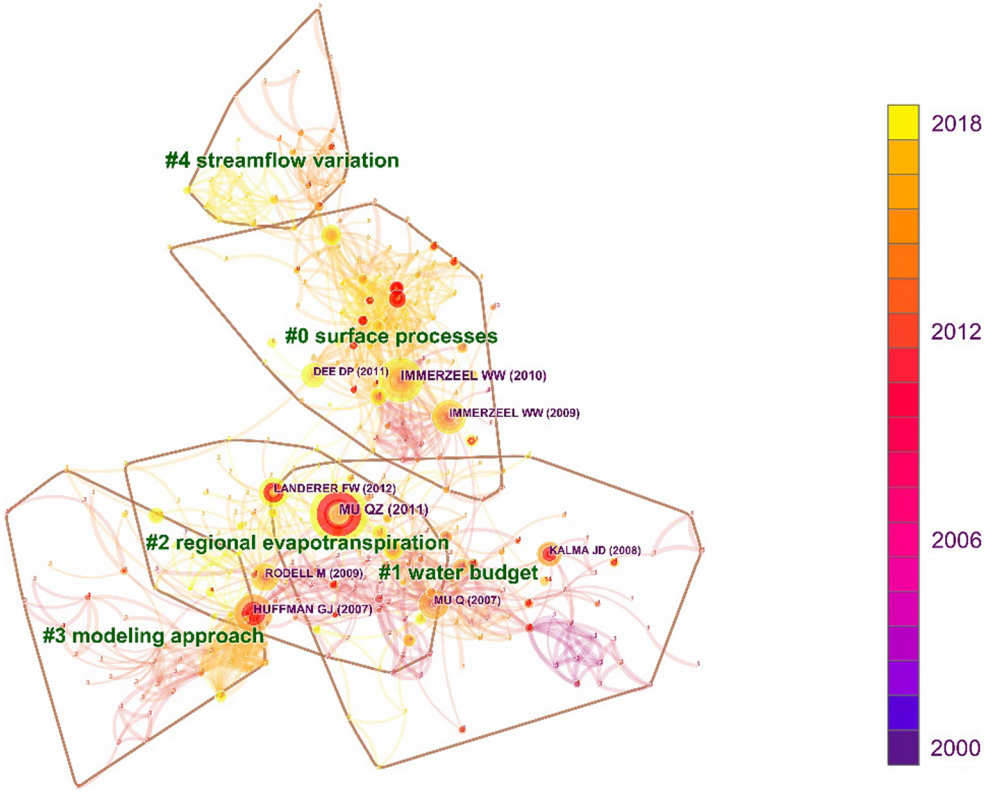

Fig. 8. A landscape view of the co-citation network.

citation papers, the key topics were also analyzed to serve as a supplement for the keyword analysis. In the following discussion, we primarily focus on the most significant five clusters and the top 10 highly cited articles over the period of 2000 to 2018 (Fig. 8). The study of remote sensing application in water environmental processes mainly focused on surface process. Among these surface processes, snowmelt-runoff is one of the most attracted surface processes. As a major part of the cryosphere, snow cover represents a valuable terrestrial water resource. In the context of climate change, the dynamics of snow cover play a crucial role in rebalancing the global energy and water budgets. Considering the significance of snow meltwater in water supply and domestic usage downstream, evaluation of snowmelt-runoff simulations is required in order to perform reliable simulations of hydrological processes. However, it's still hard to directly estimate snowmelt runoff by remote sensing technology, this has made most studies focus on runoff simulation based on remote sensing data and water balance method especially in parts of the world where ground-based monitoring networks are sparse. Fortunately, future mission Surface Water and Ocean Topography (SWOT) is scheduled to be launched in 2021, which is expected to be the first survey of surface water like river discharge and lake, reservoir, and wetland storage. When SWOT data become available, a new breakthrough of water cycle will become possible. In addition, with the continuous of warming, snowmelt-dominated regions will face even more austere water supply security challenges, permafrost thawing, glacier melting and its contribution to runoff variation and sea level up will continue to be popular research subjects. Overall, remote sensing, as long-term records become available, will offer the opportunity for better understanding of water environmental processes and its interaction mechanism with climate change.

4.2. Emerging trend and direction analysis

The analyses based on the keywords and highly cited papers can provide details of the field and analyze the key topics, but they may not be adequate for analyzing the newest development trends of this field. Both analyses neglect the frequency of keywords and reference increases over time, hence the latest emerging articles will not be retrieved. To capture these themes and forecast directions, burst detection was applied to detect rapidly emerging trends in articles. The citation frequency of these articles increased suddenly in different years, and these surge trends remained until 2018, i.e., the last year of the study period. The analysis of these references can offer more insight into research hotspots and emerging trends (Table 1).

Currently, terrestrial water storage (TWS) observed by the Gravity Recovery and Climate Experiment (GRACE) satellite mission has demonstrated its great potentials for drought monitoring and evaluation of groundwater recharges (Li et al., 2012; Wada et al., 2010), which may become a hot area in the years to come. Correspondingly, more and more scholars put their attentions on the accuracy of GRACE TWS estimation and how to rigorously quantify the TWS estimates for hydrological applications (Landerer and Swenson, 2012). Glacier change research has gained considerable attention by climatologist and hydrologist over the last several years, particularly warming-induced glacier melting as well as its contributions to runoff variation from surrounding river and sea level rise (Gardner et al., 2013; Lutz et al., 2014). However, the lack of complete understanding of glacier variations include mass, area and length, makes glacier research under a changing climate a challenge for a long period in the future (Bolch et al., 2012). In addition, recent studies showed that climate change may even accelerate "drought propagation" by increasing the frequency and intensity of drought events. As a result, the growing concern has triggered research on drought assessment and drought monitoring based on remote sensing data (Houborg et al., 2012; Karnieli et al., 2010). However, to date, there is no universally accepted definition and understanding of drought events. A drought cannot be defined as the lack of precipitation, but rather as a negative hydroabnormity of each watershed process; for instance, abnormally low streamflow in rivers, wetland degradation and underground water depletion, etc. Looking

Table 1
Articles published in 2000–2018 with subsequent citation bursts.

Reference	Title	Journal	Burst	Duration	Range (2000–2018)
Landerer and Swenson (2012)	Accuracy of scaled GRACE terrestrial water storage estimates	Water Resource Research	5.50	2016–2018	
Gardner et al. (2013)	A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009	Science	3.51	2016–2018	
Parajka and Blöschl (2008)	The Value of MODIS Snow Cover Data in Validating and Calibrating Conceptual Hydrologic Models	Journal of Hydrology	3.36	2015–2018	
Karnieli et al. (2010)	Use of NDVI and Land Surface Temperature for Drought Assessment: Merits and Limitations	Journal of Climate	2.94	2015–2018	
Houborg et al. (2012)	Drought indicators Based on Model-Assimilated Gravity Recovery and Climate Experiment (GRACE) Terrestrial Water Storage Observations	Water Resource Research	2.94	2015–2018	
Entekhabi et al. (2010)	The Soil Moisture Active Passive (SMAP) Mission	Proceedings of the IEEE	2.79	2015–2018	
Lutz et al. (2014)	Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation	Nature Climate Change	2.53	2015–2018	
Li et al. (2012)	Assimilation of GRACE Terrestrial Water Storage into a Land Surface Model: Evaluation and Potential Value for Drought Monitoring in Western and Central Europe	Journal of Hydrology	2.52	2015–2018	
Wada et al. (2010)	Global Depletion of Groundwater Resources	Geophysical Research Letters	2.52	2015–2018	
Kerr et al. (2012)	The SMOS Soil Moisture Retrieval Algorithm	IEEE Transactions on Geoscience & Remote Sensing	2.42	2015–2018	

forward, other occurrence forms of drought are of great significance that require special attention. More importantly, both the results of co-citation analysis and burst detection indicated the SMAP mission and SMOS mission have motivated soil moisture retrieval. Although the SMAP radar stopped transmitting after only 3 months of operation, the performance of SMAP radar data has recently been evaluated with encouraging results (Pan et al., 2016). For watershed scale studies, the coarse resolution of passive inversion is a problem demanding a prompt solution.

5. Conclusions

This study presented the application of remote sensing to water environmental processes under changing climate from 2000 to 2018. The number of related publications rose at an average annual growth rate of 15.97% over the past 19 years, indicating that the breadth and depth of research on water environmental processes using remote sensing have improved significantly. In addition, this domain is a highly interdisciplinary field that covers a wide range of interests, from water resources to environmental science, geology, engineering, ecology, and agriculture. However, the lack of collaboration between countries will limit augmentation of remote sensing data availability. Enhanced international collaboration will constitute important assets.

Research on water environmental processes based on remote sensing has undergone tremendous changes in recent years. The objects of study shifted from single-factor analysis to simulation of the whole basin or watershed hydrological process as well as its influencing factors. The research methods have evolved from traditional ground-based observations to independent use of remote sensing observations (some use them both). The application of remote sensing has shifted from simple data acquisition toward a higher stage of self-verification and cross-validation of datasets. Moreover, the early studies tended to be focused more on algorithm development by dedicated teams; hence, these articles tended to appear in remote sensing and engineering journals. At present, the research themes contain more application of remote sensing products, and related articles are usually included in environmental science and water resource journals. Among these research themes, climate change is undoubtedly the fastest rising topic. Climate change and its complex interaction with water environmental processes, as well as other occurrence forms of drought require special attention in future studies. To meet the development trend and demand of these integrated studies, the consistency or transferability among satellite data needs to be improved. Looking forward, the design of comprehensive observation missions, datasets of different variables with the same spatial resolution, improvement of the universality of existing products and development of data assimilation techniques are most needed for the application of remote sensing.

Compared with the traditional reviews from experts, the analyses based on CiteSpace in this paper also have certain limitations. Some limitations existed in CiteSpace, for examples, similar keywords which should be merged have to be combined manually and the first author and corresponding author cannot be distinguished clearly. In addition, clustering of co-cited articles can only count the most commonly used keywords or phrases without citation context analysis. While it is faithworthy that with the sustained efforts of the research group of CiteSpace, this software will overcome these drawbacks and present more accurate and deep knowledge domain in the future.

Conflict of interest

The authors declared that there is no conflict of interest.

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